Science and Technology in China
Required Reading

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Foreword

This manuscript constitutes the **Required Reading** for a module on science and technology within the course *Understanding China* offered online to all CUHK students, starting in the academic year 2022–23.

Several topics from the online lecture of about two hours are presented at a level of detail and depth appropriate to a university course. To keep to a manageable length (about 28 pages excluding Front Matter and blank space in the book-style layout), only a subset of topics are selected, and these are organised as almost stand-alone vignettes, sacrificing the ligaments that connect to contexts and across topics — which are provided by the oral lecture and the Supplementary Reading (see below).

The Required Reading is one out of three related manuscripts.

A : the **Supplementary Reading**, best described as my own learning journal as I gathered, organised and digested the material.

B : the **Required Reading** here, essentially an excerpt from Version A.

C : the **Speaking Script** for the oral lecture.

As material for a general education course, there is no claim to originality in any of these versions, except for personal views in a small number of places.

Because these lectures are for all CUHK students, including international students, the manuscripts are in English. However, a Chinese version is also provided for the Required Reading. The Bibliography can be found in the Supplementary Reading.

Acknowledgment

I am grateful to Prof Alan Chan and Prof Isabella Poon for inviting me to contribute to the course *Understanding China*, and am honoured by the company of the other lecturers in the course. Prof Thomas Lee and his colleagues at the Office of University General Education, in particular Ms Annie Cheung, have kindly provided coordination and support.

Gratitude goes to Prof Wong Suk-Ying, who was in charge of student exchange, for giving me the impetus to move beyond a long-standing but admittedly casual interest in the subject. It was in 2018 that she mooted the idea of putting together such a course to serve, in the first instance, exchange students from Stanford expected to come to CUHK. The course was accordingly developed and has been offered for three cycles, in the fall terms of 2019, 2020 and 2021. Events beyond anyone's control meant that only a small number of students in that original target group were able to join the course, and only in 2021. Nevertheless, the course was well received by CUHK students registered within the category of Chinese Cultural Heritage in University General Education. The dual-listed course was placed within the responsibility of the Centre

for China Studies, and I thank Prof Jan Kiely and the office staff for support. In particular, thanks go to Ms Yang Yiwei, who acted most enthusiastically and capably as TA in 2020 and 2021.

The notes that follow owe much to fellow teachers in that course, and in many places draw heavily on their lectures. In this category I must especially thank Dr FC Chen, who, unlike me, is a real expert on this subject. The course design in particular relied much on his advice. The other teachers included Dr KM Pang, Prof CT Lai, Prof Jiang Yuanan and Prof Fred Cheung, as well as Prof CA Daniels from HKUST. Not all of the topics they covered could be brought within a two-hour lecture, but my understanding of the topic as a whole has been enhanced through their lectures and their writing. More specific acknowledgements can be found in those sections that draw from their parts of the course.

In writing up these notes, I have been especially helped by Dr KM Pang and also Dr WH Wong, in pointing me to sources, correcting some of my mistakes, in proofreading and in the graphics (including graphics for the video recordings). Dr FC Chen, Prof Fred Cheung, Prof Thomas Lee and Prof YS Leung have given valuable input to the manuscript. Prof Xie Zuowei, Prof MC Chu and Prof Dennis Lo have commented on some parts of the manuscript.

Turning the material into an online lecture with audio-visual bells and whistles is an arduous task, and one which those of us brought up to think of the written word (and the printed page) as the default medium of academic discourse do not find at all easy. I am most grateful to the e-learning support team: Ms Judy Lo and her colleagues Ms Pui Lam So, Mr Rudi Chow from ITSC, and Ms Rita Dong from CLEAR. Dr KM Pang and Dr WH Wong have kindly agreed to take charge of of the related student assessment.

It has been several months' work in 2021 and 2022, and the manuscript seen in the ensuing pages would not have been possible without all the help and inspiration so graciously offered. Responsibility for any remaining errors, and for opinions expressed or implied, is mine.

Message to students

Given that you should have already listened to the oral lecture, you can go through the Required Reading quite quickly, in the first round treating the material as you would a newspaper or a magazine, without getting bogged won on minor details (and the footnotes). Topics in the oral lecture not covered here can be found in the Supplementary Reading. In particular, the parts on mathematics and astronomy are commended to those with interest in these subjects; they are left out of the Required Reading because some of the necessary technical background may not be available to every undergraduate.

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Chapter 1

The Four Great Inventions

The Four Great Inventions of pre-modern China — magnetism, gunpowder, paper making and printing — are said to have "changed the whole face and state of things throughout the world" (Bacon, 1620, *Novum Organum*, cited in *SCC*5-7, p xxx).[1]

1.1 Magnetic compass

(See *SSCC*3, Chapter 1)

Ronan and Needham regard magnetism as "the greatest Chinese contribution to physics".

Magnetised objects might have been used in divining boards from the first century. Accounts of magnetic phenomena and the use of the compass in navigation date from a thousand years later (*SSCC*3, p 2). Detailed observations and records included: the way lodestone points, the two polarities, that magnets do not align exactly north–south,[2] that iron can be magnetised (but not copper, nor pottery). Clever ways were invented to reveal the tiny turning tendency: resting a magnetised spoon on a smooth tablet, floating a magnetised object on water, making thin and sharp needles, suspending a magnetised needle from a thin thread of silk.

Yet the attempts to understand the phenomena — what we would now call basic science — were primitive, even pathetic:

> If you think that because the lodestone can attract iron you can also make it attract pieces of pottery, you will find yourself mistaken ... The lodestone can attract iron but has no effect on copper. Such is the motion of the Dao.
>
> (*Huainanzi* 淮南子, c. 139 BCE, cited in *SSCC*3, p 3)

[1] Actually Bacon did not include paper making as a separate entry.
[2] What we would now call the magnetic declination.

One is struck not so much by the inadequacy of the explanation, but by the apparent satisfaction with which it was viewed.[3]

The widest use of magnets was in divination, and also geomancy (*SSCC*3, p 6). We need not apologise for the superstition of our ancestors, but our contemporaries going around with a magnetic compass[4] for this purpose are surely an embarrassment, and in counterpoint to Needham, perhaps "the greatest Chinese insult to physics".

The use of the magnetic compass in navigation was recorded from the 11th century (*SSCC*3, pp 27–). The most celebrated maritime explorations — though by no means the earliest — were those of Admiral Zheng He 鄭和,[5] who lived almost a century before Columbus. Zheng He led a huge fleet (each ship many times larger than those of Columbus) "seven times down the southern oceans", visiting Southeast Asia, India, Arabia and once going as far as Africa. The use of the compass was clearly recorded in ship journals.

The magnetic compass became even more important in the hands of the Europeans, who combined it with ship-building skills, a seafaring spirit, and powerful financial incentives to sail the high seas, leading to the European discovery of the Americas. Ironically, Columbus was trying to reach China (and India) but was unaware that the magnetic compass that he used was a Chinese invention.

1.2 Gunpowder

(See *SCC*5-7)[6]

Gunpowder arose out of "those ancient practices of religion, liturgy and public health which involved the 'smoking out' of undesirable things in general" (*SCC*5-7, p 1) going as far back as the 7th century BCE (*SCC*5-7, p 1).

The subject is referred to in Chinese as *huoyao* 火藥. The word *huo* 火 (fire) more accurately captures the range, from slow burning to violent explosions obtained by tuning the ingredients. The word *yao* 藥 ("drug") reveals that explosives were linked to pharmaceuticals. The ingredients were listed as in herbal prescriptions.

The main ingredients of gunpowder were saltpetre, sulphur and charcoal: sulphur is easy to ignite, charcoal burns, and saltpetre (potassium nitrate,

[3]Note added when preparing the Chinese translation: Although the above quote is taken correctly from *SSCC*, I cannot find the phrase corresponding to "the motion of the Dao" in *Huainanzi* itself. This fragment is also missing in an authoritative Chinese version of *SSCC* by historians of science at Jiaotong University. There could have been a mistake by Needham, or there could be different versions of *Huainanzi*. Be that as it may, the implication remains valid about the types of explanations that were accepted.

[4]In this use called a *luopan* 羅盤.

[5]By calling him "Admiral", the English-language literature erroneously conveys the sense of military expeditions. In Chinese, he is known as "Eunuch Zheng He", and his vessels were called "treasure ships".

[6]As far as I can tell, *SSCC* never got as far as this part (namely Volume 5) of the original series.

KNO_3) supplies oxygen for combustion. It was about 850 CE when the "systematic, if obscure, investigation of Daoist alchemists" (*SCC*5-7, p 15) seeking "elixirs of life and material immortality" (*SCC*5-7, p 7) accidentally and ironically stumbled upon this lethal combination. The proportion eventually settled upon something like saltpetre 75, sulphur 15, charcoal 10, after impressively systematic investigation (*SCC*5-7, pp 94–108).

The story of additives, more appropriate to a witch's brew, is less flattering. The *Wujing Zongyao* 武經總要 (*The Consolidated Military Principles*) of about 1044 (*SCC*5-7, pp 118–119) recorded pine resin, sprinklings of hemp roots, dried lacquer, arsenic, white lead, bamboo roots, minium,[7] yellow wax, clear oil, tung oil and thick oil, even dried human faeces to generate "a disagreeable dust" (*SCC*5-7, p 125).

Many later advances, including good metallic gun barrels, were predominantly European. The role of artillery and skills in its use gradually expanded from the 13th to the 15th century; castles became difficult to defend, contributing to the decline of feudalism. When China was invaded in the 19th century, the balance of fire-power had already shifted dramatically against the inventors of gunpowder.

Guns[8] made a huge impact in European intrusions into in Central and South America, including the total devastation of Aztec society. The "conquest" of the American West, romanticised in so many cowboy-and-Indian films, was a story of European guns overwhelming native American bows and arrows. The Anglo–Zulu war (1879) was a tragic episode of spear-wielding natives decimated on their own land by English rifles.

1.3 Paper making

(See *SCC*5-1, Chapter 32)

The earliest writing probably appeared in Mesopotamia before 3000 BCE, using reed styluses on wet clay tablets which were then allowed to set. Within a few centuries, the Egyptians had developed papyrus scrolls to write on. Parchment and velum (different forms of leather) were known but expensive, and writing was by no means common.

The earliest recorded Chinese writing (about 1600–1300 BCE) was carved on animal shells and bones, bronze vessels, stone tablets, and more conveniently on bamboo or wood slats. By about 220 BCE, the ink brush had been invented, and writing was executed on bamboo (which does not absorb well) and then on silk (absorbent, but expensive). The invention of paper-making, by Cai Lun 蔡倫 in the second century CE, made the written word much more accessible.

Paper-making technology is in its essence unchanged to the present day. The raw material (wood, bamboo, jute, rags or straw) is boiled in water to loosen the fibres, and then pounded into a paste. A plane sieve is run through the suspension to bring up a thin sheet of crisscrossed fibres, which is then

[7] An oxide of lead found as a mineral, and used in very small quantities as a medicine.

[8] And also other factors such as a colonising mindset and superior military organisation.

dried under the sun, gently peeled off and then pressed. About this process several remarks can be made. (1) There was no fundamental science. (2) The multiple technical steps required patient trial and error. (3) Once the method was mastered, it could be passed on and replicated, leading to a cottage industry. These features are common to many technological achievements in traditional China.

1.4 Printing

(See *SCC*5, Chapter 32)

Undoubtedly printing originated from making imprints with carved seals and from ink rubbings of stone. The use of carved wooden blocks (not later than the 7th century CE) was not a great leap, and had no identifiable inventor. But carving was tedious, so printing was mostly limited to sacred Buddhist scripture.

Movable type was invented by Bi Sheng 畢昇 around 1045: a typeface (porcelain, wood or later metal)[9] was made for each character, and these were placed in the proper order on a rack, in lieu of a carved wood block. The advantage, though significant, was limited: there are thousands of Chinese characters, and each copy of the same typeface had to be individually carved. Therefore wood block printing continued to be used for many centuries. Bi Sheng's invention was documented in *Mengxi Bitan* 夢溪筆談 of 1166, itself printed with this technology.

The printing press of Gutenberg (c. 1450) contained a number of advances. (1) Metallic movable type was used (probably invented in Korea in the 13th century, and also used in China). The better durability is offset by the greater difficulty in carving, so adoption was limited. (2) Importantly, multiple copies of a typeface were made by pouring molten metal, i.e., by *casting* rather than *carving*. This method was apparently known in China before Gutenberg, though not widely used and not even much emphasised.[10] (3) Gutenberg integrated the printing process, especially with a mechanical press inspired by the wine and olive presses of Europe. (4) Improvements in metallurgy had led to alloys (especially those containing lead) that had a lower melting point and could therefore be more easily handled.[11] (5) Other refinements included ink that flowed more smoothly.

These improvements, together with the advantage enjoyed by alphabetical languages in reducing the number of distinct typefaces required, led to a rapid

[9] Bi Sheng carved on clay, which was then baked into porcelain.

[10] Pan 潘吉星 (2002, pp 188-207) asserted that the metal typefaces in China were cast, because carving would surely have been too laborious. There are several reasons why he had to resort to such an indirect argument. First, metallic movable type was hardly used for books, but mostly for the serial numbers in paper money, so extant evidence was scarce. Second, historical accounts were often careless in using the word *ke* 刻 (carved) when they probably meant *zhu* 鑄 (cast), showing that the distinction was not well appreciated.

[11] Gutenberg, before he gained fame as a printer, was a goldsmith.

spread of printing using cast movable type in Europe, on a scale not seen in China for many centuries.

Chapter 2

The Needham question

(I am indebted to Dr FC Chen for much of the material in this section.)

Despite the pride often taken in the inventions of ancient and medieval China, by the 19th century, it had become abundantly clear that China was lagging behind Europe in science. One is thus confronted with the question "Why did modern science fail to emerge in China?", or "Why did Chinese science lag behind Western science?" Although often associated with the name of Needham, the query was first raised earlier.

2.1 Raising the question: Ren Hongjun

We pick up the tale with the students pursuing studies abroad in the early Republican years. Cornell University was a destination for quite a number of Chinese students. In 1914, a group of Chinese students there formed a Science Society of China, in which the most active was Ren Hongjun (HC Zen) 任鴻雋 .[1] While the question of a lag in science was obviously in the minds of many Chinese students, it was apparently Ren (1915) who put it forcefully into print, in an article "On the cause why China had no science", published in the inaugural issue of the journal *Science* (*Kexue* 科學) which he founded.[2]

[1] Ren had an interesting career, starting with the first level (*xiucai*) 秀才 in the imperial examination system, studying chemistry in Japan, engaging in revolutionary activities in the final years of Qing 清 rule, serving in the office of the President when Sun Yatsen 孫逸仙 、孫中山 was briefly in power, then going abroad again, first to Cornell and later to Columbia. Armed with a master's degree, he returned to China, and became a professor at Peking University 北京大學. In the 1930s, he was President of Sichuan University 四川大學, and later served as Secretary-General of Academia Sinica 中央研究院. He was interested in the history of science, believing that only an understanding of the historical processes could foster a scientific spirit. He was a close friend of Hu Shih 胡適; classmates in high school, they both attended Cornell and then Columbia.

[2] The journal ran into difficulties in the early 1950s, was briefly revived in 1957, still under Ren, and then stopped again in 1960 for political reasons. It was relaunched in 1985, by then as an official publication, and under the editorship of Zhou Guangzhao 周光召, a distinguished theoretical physicist who was one of the youngest members involved in the atom bomb project,

Several remarks can be made about this article. (1) The investigation was obviously motivated by the mission to "save the nation". (2) Although Ren referred to "science" rather than "modern science", he implicitly meant the latter, since he wrote that Western science had been around only 300 years. (3) His tentative answers were the lack of scientific method, especially the inductive process based on experimentation, and a tendency to vague abstractions rather than precision, as well as a lack of curiosity about causes. (4) In this article, and at greater length in later ones, he pointed to the scientific spirit[3] and its apparently weakness in China. (5) There is much to be said for Ren's point of view, but his writings and those of other contributors to the debate were largely at the level of opinions and conjectures — ironically the very scientific spirit and respect for evidence that they pointed to were not yet to be found in their own practice as putative historians. (6) He wrote in elegant classical Chinese (as befitted a *xiucai*) — the push for the vernacular form was just beginning. But an interesting question is whether the somewhat vague and loose arguments in this article[4] (the same weakness that Ren criticised in ancient Chinese investigations into nature) were intrinsically tied to the classical style of expression.

2.2 Needham the person

Joseph Needham (1900–1995), known in China as Li Yuese 李約瑟, started his career as a biochemist in Cambridge. During the Second World War, he was sent by the Royal Society[5] to Chongqing 重慶 (the wartime capital) to head an office for science cooperation. There he developed his interest in early Chinese science, already kindled by a Chinese student he had in Cambridge, Lu Gwei-djen (Lu Gweizhen) 魯桂珍 — later to become his lifelong collaborator and, in old age, his second wife. A good introduction to Needham can be found in the citation for his honorary doctorate from CUHK (1983).

His fame derives from his monumental study of early Chinese science. Needham was a scientist and a Sinophile.[6] He also had Marxist inclinations — by no means rare among British intellectuals in the 1930s.[7] However, he was not a Marxist in the sense of supporting the dictatorship of the proletariat; rather, he was receptive to the Marxist view that the course of history was strongly influenced by the economic and social structure of society, though he did not subscribe to the idea of universal historical laws.[8] The more he worked

and who later rose to become President of CAS and then one of the Vice Chairmen of the National People's Congress.

[3] Apparently Ren was the first to use the term *kexue jingshen*.

[4] The article, in typical classical style, appealed to allusive and correlative reasoning. In arguing that science needed both deduction and induction, he made the parallel with a chariot needing two wheels and a bird two wings.

[5] He went in 1942, after being elected FRS in 1941.

[6] The best known of his biographies is entitled *The Man who Loved China* (Winchester, 2008).

[7] See for example the famous story of "the Cambridge Five" who spied for the USSR.

[8] "... I have never been sympathetic to that other trend in Marxist thinking which has sought for a rigid and unitary formula of the stages of social development which all civilisations

on Chinese history and civilisation, the more he became enamoured of Daoist philosophy. His Marxist and Daoist tendencies would colour his views about science in China.

2.3 The *magnum opus*

Early assessments of science and technology in China suffered from a failure to sufficiently distinguish between traditional science and modern science. There was therefore a tendency, especially among Western scholars, to assume that Chinese science[9] had *always* lagged behind European science. This assumption was in part due to ignorance, but there was also a deep-seated prejudice: that some civilisations were intrinsically inferior ("witness their inferior science!"), or, with a slight twist, that tropical and humid climates were not conducive to higher mental processes (applied at least to the case of India if not China); "racism" would be a just label, and Euro-centrism a kinder euphemism. Such a belief would give an easy answer to the question at hand. Needham's multi-decade project showed, beyond a doubt, that *early* Chinese science could boast of a host of achievements, in many cases leading the West — and thereby extinguished any racial (or climatic) argument that would have implied the same gap through all of history.[10] This definitive demonstration is important, for there remains to this day a resistant strain of racism which would claim that non-White science cannot — or cannot be allowed to — match or surpass Western science.

The life-long work was published in *Science and Civilisation in China* (Needham, 1954), here abbreviated as *SCC*. Even professional historians of science would find the entire series of some twenty books daunting; the tomes are more like source books of primary research. A more accessible version is the *The Shorter Science and Civilisation in China* (Ronan, 1978),[11] here abbreviated as *SSCC*, which is a précis of *SCC*.[12] Though "shorter", *SSCC* still runs to five volumes.

SCC, by its very meticulous examination of primary evidence as well as well-established literature, paints a picture of traditional Chinese civilisation that was rich in inventions and in science. Needham the Sinophile was given to exaggerations (e.g., in claiming that some European inventions were derivatives when they were just as likely to have been independent, and in giving excessive credit to vague statements in ancient Chinese texts as precursors of modern science), but even with such excesses discounted, one cannot deny that traditional Chinese science, as an example of *pre-modern* science, i.e., in comparison with

'must have passed through'." (Needham, 1969, p 192).

[9] And also science in other non-European civilisations.

[10] "From the beginning I was deeply sceptical of the validity of any of those 'physical-anthropological' or 'racial-spiritual' factors which have satisfied a good many people." (Needham, 1969, p 191).

[11] Sometimes the authorship is attributed to Ronan and Needham.

[12] Not covering additions to *SCC* after the death of Needham.

Europe before the Scientific Revolution, was robust, in a nontrivial number of domains even leading.

This conclusion does not answer the key question at hand, but only tilts the emphasis to *modern* science, and by implication, to the question placed side-by-side with its obverse: Why did modern science arise in Europe but not in China, when the latter was (apparently) by no means lagging behind, say in the 16th century?

2.4 Needham's thesis

Needham did not, in fact, directly address in *SCC* the question that came to bear his name — *SCC* was a compilation of evidence rather than any excursion into hypotheses. Rather, his answer to the question was contained in lectures given over the years and recorded in essays such as those collected in *The Grand Titration* (Needham, 1969). Here we draw in particular on the essay "Science and society in East and West", first published in 1964 and reprinted in Chapter 6 of *The Grand Titration*.

As already mentioned, Needham was inclined to seek explanations in the social and economic structure: "The answer to all such questions lies, I now believe, primarily in the social, intellectual and economic structures of the different civilisations." (Needham, 1969, p 190). Needham pointed to the different kinds of feudalism in Europe and in China.

> For the purposes of the historian of science, therefore, we have to be on the watch for some essential differences between the aristocratic military feudalism of Europe, ... and those other kinds of feudalism ... which were characteristic of medieval Asia. From the point of view of the history of science we must have something at any rate sufficiently different from what existed in Europe to help us solve our problem.
>
> (Needham, 1969, pp 191–192)

He went on to quote Wittfogel's[13] idea of of "bureaucratic feudalism" in Asia, which was explained as (Needham, 1969, p 193) "the growth of a State apparatus fundamentally bureaucratic in character and operated by a non-hereditary elite upon the basis of a large number of relatively self-governing peasant communities, still retaining much tribal character and with little or no division of labour as between agriculture and industry", the social order being justified on two counts: defence and public works. The emperor exercised authority not through feudal lords, but through a non-hereditary civil service or "mandarinate". He went on to say that the Asian "bureaucratic feudalism" did not support modern capitalism and modern science — in contrast with European feudalism which was favourable to the growth of merchant guilds and hence of capitalism.

[13] " ... a more or less orthodox Marxist in pre-Hitler Germany" (Needham, 1969, p 193).

2.5 Evaluation and a more viable alternative

There is some truth in Needham's description of Chinese society, but to offer these observations as an explanation for the failure of modern science to emerge would be very much off the mark. Needham was misled by his failure to distinguish clearly between science and technology. Much of what he described as achievements in pre-modern China were really technological rather than scientific. His thesis might have some merit if offered to account for the weakness or belated rise of modern *industries* in China.

All this becomes clear when we examine the other side of the coin: the rise of Europe after the Middle Ages. The conceptual break came with the *Scientific* Revolution, with key names such as Bacon and Descartes in terms of methods of science, and Copernicus, Galileo, Kepler and Newton in terms of actual breakthroughs. It would be very far-fetched indeed to claim that the "mercantile order of society" or "productive industrial enterprises" has much to do with these giants who, of course together with many of their comrades, collectively brought Europe into scientific modernity.

To seek reasons for the emergence of modern science in Europe would be a huge task in itself, and there will not be sharp and unique answers. A modern treatment, keeping the contrast with China implicitly in mind, can be found in Chen 陳方正 (2021);[14] a good overview is found in the relatively brief Introductory Remarks (*ibid*, pp 4–34). One surely must point to the legacy of Greek philosophy (transmitted through and enhanced by the Arabic world), including Platonic ideals, Aristotelian logic, Pythagorean and Euclidean mathematics, and a tradition of curiosity and of seeking causes and laws. It is clear that Kepler's ellipses and Newton's point masses belong to the Platonic world — to which any notions of social or economic order are surely irrelevant. Indeed, Ren had already written about the scientific spirit. One must pay attention to this cluster of factors in thinking about this important transition in European history — and in seeking reasons for the failure of modern science to emerge in China.

Nevertheless a small twist to Needham's thesis may hint at a factor of possible contemporary relevance. A capitalist or mercantile society is decentralised and pluralistic. Different individuals strike out in multiple (intellectual) directions — some of which might lead to breakthroughs. A bureaucratic society tends to be more monolithic, closely adhering to a single agenda. This remark should not be forgotten in the present age, when over-emphasis on large projects and fashionable directions threatens to sideline genuine innovation.

[14]The author Chen Fangzheng (FC Chen) 陳方正 is one of the key contributors to a 3-unit GE course in CUHK on science and technology in China, from which much of the content of this article is drawn.

Chapter 3

The bombs and the satellite

Despite many challenges in society, there were notable achievements in the first three decades of the PRC in major projects. Some of these are sketched below, starting with "Two Bombs, One Satellite" (*liangdan yixing*) 兩彈一星 — two prongs of one single national strategy.[1]

3.1 Nuclear weapons

The dates for the first successful tests of the fission and fusion bombs[2] by the five major powers (the Permanent Members of the UN Security Council)[3] are as follows.

Nation	Fission	Fusion
US	1945	1952
USSR	1949	1953
UK	1952	1957
France	1960	1968
China	1964	1967

Table 3.1: Dates of first explosion of nuclear device

Why did China feel a strong need for the bomb, when there were urgent and

[1] Originally, *liangdan* 兩彈 referred to nuclear bombs (*yuanzidan* 原子彈, including both A-bomb and H-bomb) and the missile (*daodan*) 導彈; later it came to mean the A-bomb and the H-bomb as two items, with the missile lumped with *yixing* 一星 — as would be suggested by the standard English translation.

[2] Fission bombs, conventionally called "atom bombs" or "A-bomb", work by splitting heavy nuclei such as uranium. Fusion bombs, conventionally called "hydrogen bombs", "H-bombs" or "thermonuclear bombs", work by fusing light nuclei such as hydrogen. The latter is many times more potent.

[3] At the time, the Chinese seat was taken up by the KMT government in Taiwan. The USSR of course no longer exists as such. British scientists were involved in the Manhattan Project; the date 1952 here refers to the independent British effort.

competing demands in society? How did China manage the huge scientific and technical challenge, when the country was so poor[4] and the pool of scientific talents so small? This makes for an interesting case study into the conditions necessary for (at least some aspects of) science and technology development. A comprehensive reference is *China Builds the Bomb* (Lewis and Xue, 1991).

Upon the conclusion of World War Two, Korea (formerly controlled by Japan) was occupied by the Soviet Union and the US. Civil war between the North and the South broke out; US forces joined on the side of South Korea, and at one point were pushing towards China, whereupon, in 1950, less than one year after PRC was established, Chinese forces crossed the Yalu 鴨綠江 to fight alongside the North Koreans, pushing the better-equipped US army back to a stalemate at the 38th parallel. An armistice was signed in 1953. Apart from worries about China being invaded,[5] there was fear that the US might use nuclear weapons — there were overt threats, and the US President had to rein in his theatre commander. Thus, there quickly developed a consensus among the Chinese leadership that national security required nuclear deterrent capabilities; the decision was made in 1955 to launch a top-priority project to build the bomb.

Name	Born	Training	Mentor
Wang Ganchang	1907	PhD Berlin 1934	Meitner
Guo Yonghuai	1909	PhD Caltech 1943	von Karman
Qian Sanqiang	1913	PhD Paris 1940	Irene Joliot-Curie
Peng Huanwu	1915	PhD Edinburgh 1945	Born
Cheng Kaijia	1918	PhD Edinburgh 1948	Born
Deng Jiaxian	1924	PhD Purdue 1950	Belinfante
Zhu Guangya	1924	PhD Michigan 1949	Wiedenbeck
Yu Min	1926	BS Beida 1949	Zhang Zongsui
Zhou Guangzhao	1929	BS Beida 1951	Peng

Table 3.2: Key leaders of nuclear weapon project.
The names cited are, in the first column: 王淦昌, 郭永懷, 錢三强, 彭桓武, 程開甲, 鄧稼先, 朱光亞, 于敏, 周光召; and in the last column 張宗遂.

The careers of the notable scientists (mostly physicists) pivotal to the bomb project (Table 3.2)[6] reveal much about the progress of science and technology capacity over several generations. A first generation of returnees (not shown) had helped to establish credible departments at Beida 北大, Tsinghua 清華, Zhejiang 浙大, and later Southwest Associated University 西南聯大, where those listed here obtained very good undergraduate education. All except the last two

[4] In 1960, per capita GDP in China was USD 90, compared with USD 3,000 for the US (World Bank, 2021a).

[5] The worries were understandable — in the 110 years up to 1950, China had seldom been free from foreign armies on its land.

[6] There is an official list of 23 heroes for the bomb and satellite projects; the names in Table 3.2 are the main ones for the bomb.

went on to top graduate schools abroad, mentored by the leading scientists of the age.[7] The younger ones were trained domestically: Yu did his BS in Beida, and went on to graduate school in Tsinghua under Zhang Zongsui; he was recruited to CAS, where he was mentored by Peng. Zhou did his BS also at Beida, and went on to graduate work under Peng; later he went to Dubna for research.[8] Guo was not a nuclear physicist. His expertise was mechanics (his contribution was to characterise the explosion) and his mentor, von Karman, was the undisputed world authority in aerodynamics.

Nevertheless, one must acknowledge a significant gap. In terms of contributions to basic science, these national heroes could not compare with their counterparts associated with the Manhattan Project, e.g., Oppenheimer, Bethe, Fermi, Lawrence, Bohr and Peierls, or even Feynman, who was then a very young man.[9] This observation illustrates that truly original science is one major step beyond achievements such as developing nuclear bombs after others had already done so — a point often not appreciated by the public.

The US had accused the Soviet Union of having stolen nuclear secrets,[10] but there was no such allegation in the case of China, if only because no Chinese scientist had ever been close to the Manhattan Project. Indeed, in the 1970s Deng Jiaxian confirmed to CN Yang 楊振寧, his friend from childhood, that the atom bomb was built without foreign help,[11] a statement that moved Yang to tears (Yang, 2021); note that Soviet assistance had been withdrawn across the board in 1960. For the H-bomb, the situation was even more plain — the Chinese design, mainly due to Yu, was different in significant respects.

However, it must not be thought that nuclear physicists did all this alone. Making the bomb was a huge national and multidisciplinary effort: geological surveys for uranium, mining for ores,[12] chemical extraction of uranium, isolation of the tiny proportion of U-235 (the active isotope) by gas diffusion, as well as assembly into a bomb. The tasks were challenging, especially given the low level of technology throughout the country, and the state of the economy at the time. A nontrivial percentage of national GDP had to be committed, with belt-tightening in other sectors, made possible by a strong will in the country and especially within the CPC that foreign armies must never be allowed on

[7] Meitner was (together with Frisch) the first to understand nuclear fission; Irene Joliot-Curie was the daughter of Marie Curie and herself a Nobel Laureate; Born was one of founders of quantum mechanics and a Nobel Laureate (and my doctoral supervisor's supervisor's supervisor). Belinfante, though less known to the general public, has the energy-momentum tensor in electromagnetism named after him. Wiedenbeck was the author of a widely used text on experimental techniques.

[8] Zhou would later become President of CAS and upon retirement was elevated to vice-chair of the National People's Congress (NPC).

[9] I have the good fortune to know the youngest in each list: Feynman was one of my teachers (Feynman, 2005, p 252) and Zhou Guangzhao had visited CUHK multiple times, and was awarded an honorary doctorate in 1991. My path also crossed with Peierls' many years later (Peierls, 1991, p 40).

[10] And had consequently executed the Rosenbergs for spying.

[11] There was a rumour that the American physicist Joan Hinton was involved. Hinton was living in China at the time, working as a dairy farmer.

[12] In these domains the geologist Li Siguang 李四光 was a leading figure.

the soil of China again. Policy directives came from the State Council, and the whole project, spread over many laboratories, was placed under military coordination, with Marshal Nie Rongzhen 聶榮臻 in charge.[13] The successful test of the A-bomb in 1964 was met with jubilation, and was followed by the H-bomb only three years later.[14]

3.2 Rockets and satellites

The nuclear weapons are always mentioned in the same breath as the satellite (*liangdan yixing*); actually the latter involved rockets and missiles as well, and gave birth to both the current space programme and also long-range missiles. Although a number of scientists were also cited as national heroes, one singular figure both led the science and groomed the team of scientists for the project.

Qian Xuesen 錢學森 (1911–2009) received his undergraduate education in Jiaotong University 交通大學, and went to the US on a Boxer Indemnity Scholarship, first to MIT and then to Caltech where he received the PhD in 1939 under the legendary von Karman, the world's foremost expert in aerodynamics and in the nascent field of rocket science. Qian was one of von Karman's star students. At the end of war, Qian most unusually gained the rank of Colonel in the US Army,[15] and was sent to Germany to assess its rocket science and to recruit German scientists. He returned briefly to China to get married, and then took up appointments in the US, first and briefly at MIT, and then to a named chair at Caltech in 1949.[16]

The atmosphere soon changed. With civil war ended in China and a degree of stability restored, Qian was thinking about visits back home; it would not be surprising that he was interested in finding out what communism was all about, and he had attended a few meetings of left-wing groups in the US. But by 1950, China and the US were at war over Korea, and McCarthyism was running amok in the US. Even Oppenheimer came under suspicion and had his security clearance revoked. Qian was questioned, but his stance was clear: he was not a communist; he was fond of the US where (until these troubles) he was treated with respect, but he had an even stronger affinity for his own country. If he had hitherto only pondered on the possibility of returning to China for a visit, his treatment at the hands of the FBI tipped the scale. He was ordered deported (which did not require a judicial process) but at the same time confined to Los Angeles. He was finally allowed to leave in 1955,[17] sailing for Hong Kong and returning through Lowu.[18] Qian's life story is very well known in China. A

[13] The natural comparison would be General Groves, who commanded the Manhattan Project. Groves was a 3-star; Nie was the equivalent of a 5-star.

[14] Thus, China was the 5th to acquire the A-bomb, but overtook France to become the 4th to have the H-bomb.

[15] He was not a US citizen, not even a permanent resident.

[16] Named chairs were rare in those days. Even in the 1960s, among the physics professors at Caltech only the two Nobel Laureates had named chairs.

[17] Probably in exchange for US airmen shot down and captured during the Korean War.

[18] So he must have passed our campus en route, though only Chung Chi was at this site in

good English-language source is *Thread of the Silkworm* (Chang, 1995).[19]

Back in China, Qian put up a proposal to establish an air defence industry, which essentially became the blueprint for the development of the sector. In 1957, he was appointed deputy director[20] of the 5th Academy (*wuyuan* 五院) under the Ministry of Defence.

The main milestones were: short-range missiles in 1960, missiles carrying nuclear weapons in 1966, and the first artificial satellite (Dongfanghong 東方紅) in 1970. To put these into perspective, the first artificial satellite was the Soviet Sputnik in 1957, followed one year later by the US Vanguard; so China was more than one decade behind. Manned spaceflight began only in 2003, over 40 years after Gagarin (USSR) and Sheppard (USA) had taken to space in 1961.

The bombs and satellite project is hailed in China as huge achievements; the highest accolades were accorded to the heroes. It was indeed a major step forward for scientific and technological capabilities of this sort, namely the ability to replicate what a handful of other nations had done some years earlier, admittedly starting from a huge disadvantage; however, little of this was truly innovative.

1955.

[19]The author, Iris Chang, became even better known for her next book, on the Japanese atrocities in Nanjing during the Second World War — a story so devastating that it drove her into depression and suicide.

[20]The director was an administrator, and Qian was in charge of all R&D.

Chapter 4

Laser, insulin, therapy for malaria

4.1 Laser

The laser[1] is now a common device; every teacher uses it to point. It works by herding photons, in other words the "bits" of light, so that they act together in lockstep rather than independently. The idea of stimulated emission (the S and E in LASER) was first proposed theoretically by Einstein in 1917. The first successful implementation for visible light was achieved in 1960 by Maiman, who is now generally said to be "the father of the laser".

In China, the first laser was built under the leadership of Wang Daheng 王大珩 (1915–2011) at the Changchun Institute of Optics and Fine Mechanics in 1961, only a year after Maiman's invention. Wang, with an undergraduate degree from Tsinghua, gained a Boxer Indemnity Scholarship for further studies in the UK, obtaining a master's degree from Imperial College in 1941 and then going on to Sheffield to pursue a doctorate. According to his own reminiscences (CAST, 2021), he gave up doctoral studies after one year, to join an industrial lab in the area of glass-making, to acquire the industrial know-how (rather than mere book knowledge) that he felt China needed. He returned to China in 1948, well trained in classical optics (i.e., the branch of optics that does not have to worry about individual photons) and skilled in making optical glass, lenses and coatings. In 1952, he founded the Changchun Institute of Optics and Fine Mechanics under CAS, and very quickly built up infrastructure and a pool of expertise.

There, Wang Daheng's former student Wang Zhijiang 王之江 made the first Chinese laser (a ruby laser) just a little over a year after Maiman's breakthrough. No doubt the achievement rode on Maiman's ideas, but some aspects of imple-

[1] As an acronym for Light Amplification for Stimulated Emission of Radiation, the word was written as "LASER" originally; with frequent use and familiarity, it became a word in its own right, and is now usually rendered as "laser".

mentation were different. Catching up so quickly was remarkable; more importantly, the Institute was *prepared*. Thus, a series of different lasers followed: He-Ne lasers and Nd-glass lasers in 1963, and GaAs semiconductor lasers in the same year, Ar ion lasers in 1964 and CO_2 lasers in 1965, YAG lasers in 1966. In none of these were Chinese scientists the first in the world. Nevertheless, the capacity had been developed to follow world trends with a very small lag, as a very credible runner-up.

4.2 Insulin

The near-absence of high-level basic science has been remarked. There was however one notable achievement that came close to a Nobel Prize (Cao, 2004).

Insulin is produced in the pancreas, and its deficiency causes diabetes; this has been known since the beginning of the 20th century. By about 1920, insulin had been extracted from the pancreas of dogs, and then cows (the latter called bovine insulin), and injection cures (or at least regulates) diabetes. This work earned the Canadian researchers the Nobel Prize in Medicine or Physiology in 1923.[2] Since extraction from animal pancreas was inefficient, scientists turned to the possibility of synthesising insulin, which is just one large molecule (molecular weight about 6,000). Chinese scientists succeeded in 1965. It was a huge project, involving three collabrating teams at the Institute of Biochemistry in Shanghai, Beida, and the Shanghai Institute of Organic Chemistry. There was no thought that any individual or unit would profit by the invention, and initially no thought of scientific awards — the idea of highlighting individuals ran counter to the collective spirit of the time.

The Cultural Revolution erupted in 1966 and external links were almost completely severed, so the breakthrough was little known abroad. It was some years later that the national leadership realised the possibility of international recognition. In 1977 the matter was formally raised in CAS and in the next year approval was given, supposedly by Deng Xiaoping 鄧小平 himself, to put in a nomination to the Nobel committee — overcoming previous hesitation about giving limelight to individuals.[3] There was a further hurdle: at most three persons could be nominated, while the insulin project in China had four recognised leaders. It was in the end decided to put up only one candidate, Niu Jingyi 鈕經義, in part because arguably contributions had also been made by European scientists (see below), with whom the prize might have to be shared. Although the nomination did not succeed, there is agreement that a Nobel Prize would not have been out of place.

Apart from early indecision to go for a nomination, the limited international exposure (i.e., "marketing") during the Cultural Revolution, and probably lack

[2]The inventors in effect gave up personal financial rights. Such ethical behaviour was exceptional in the Western world, but would have been the norm in socialist China, as will be apparent in the story below.

[3]The years 1977–1978 saw the critical turn to a policy of reform and opening up. Before that watershed, international connections were frowned upon.

of experience in writing up the nomination, there was in fact another reason that is often glossed over.[4] The Chinese team was not the first to synthesise insulin (as is often erroneously claimed), but the first to synthesise a form of insulin *with good biological activity*; the earlier European work is reviewed by Katsoyannis (1966).[5] The biological activities depended on the synthetic routes adopted, which produced different three-dimensional structures (and also different levels of purity).[6] In those days, not much was known about three-dimensional structures, so the synthetic outcomes were not planned; they were somewhat accidental, or in the case of the Chinese team, results of patient trial-and-error (Xu, 2015). That might be one reason why neither the European scientists nor the Chinese scientists won the Nobel Prize in this instance.

A quick look at the principal scientists involved will illustrate how a generation of returnees armed with overseas doctorates helped to lead national scientific efforts, passing the torch to the next generation educated domestically, and also how inter-institutional dynamics played out. The acknowledged overall leader was Wang Yinglai 王應睞 (1907–2001), PhD Cambridge 1941, then at the Institute of Biochemistry. Also there and a fair bit younger were Niu Jingyi 鈕經義 (1920–1995), PhD Texas Austin 1953, and Zou Chenglu 鄒承魯 (1923–2006), PhD Cambridge 1951; both were undergraduates at Southwest Associated University. At the Shanghai Institute of Organic Chemistry was Wang You 汪猷 (1910–1997), PhD Munich 1937. The youngest, Ji Aixue 季愛雪 (1933–1993) at Beida, was trained entirely at Beida itself. Among these five, Wang graciously bowed out, saying that he was only the administrative leader. The other two units deferred to the Institute of Biochemistry to nominate one candidate, and in the end Niu was put forward.

The European teams were relatively small. So why was the Chinese project seen as a herculean effort? First, some reagents were not available in China, and had to be produced in-house. Second, the scale of the Chinese teams allowed many different recipes to be tried to find the most effective product, illustrating the advantage of the collective system in this case.

4.3 Therapy for malaria

Tu Youyou 屠呦呦 (born 1930) won the Nobel Prize in Physiology or Medicine in 2015, "for her discoveries concerning a novel therapy against Malaria" (Nobel Foundation, 2015); the discovery was made in the early 1970s.

The achievement relates to an *ancient* therapy in traditional Chinese medicine. Tu was educated entirely in China (at Bejing Medical University, now part of Beida), and her research was also carried out entirely in China (at the China Academy of Traditional Chinese Medicine).

[4] I am indebted to Prof Xie Zuowei 謝作偉 for patiently explaining to me the intricacies. However, the views expressed are mine.

[5] In addition, the European product was based on sheep insulin, while the Chinese product was based on bovine insulin; however, this distinction is purely incidental.

[6] Almost everyone knows by now how the spike in the SARS-CoV-2 virus is critical to its properties.

Malaria is a debilitating tropical disease. For a long time, the therapeutic agent of choice was quinine and its derivatives — not very effective and in large doses causing undesirable side effects. Thus, around 1967, North Vietnam appealed to China for help in seeking possible cures.[7] In China, the Cultural Revolution was wrecking academic and research organisations, but a project responding to a call by national leaders was largely immune to the troubles, and moreover, seeking a cure from traditional Chinese medicine was very much in line with the peasant-inspired values being promoted at the time.

Scientists scoured through tens of thousands of candidate compounds, leveraging on ancestral wisdom to focus the search on the traditional Chinese pharmacopoeia for formulations described as effective against similar symptoms. Hundreds of recipes were tried, chemicals were extracted and trials performed on mice. Wormwood was apparently effective, but initial attempts to extract the active ingredient failed. At this point Tu made an important contribution: she noticed an ancient text that prescribed the herbs to be soaked overnight in cold water, rather than boiled; she therefore suspected that perhaps the active ingredient cannot withstand heat. She then tried a cold extraction route — which succeeded. The active ingredient artemisinin (known in Chinese as *qinghaosu* 青蒿素) together with its derivatives, is now the principal drug for treating malaria. Tu's team also determined the chemical structure of artemisinin, and Tu herself was the first volunteer in the safety trials.

The Nobel Prize of 2015 was fitting tribute for this work, and for the modernisation of Traditional Chinese Medicine (TCM). It gave recognition to research carried out entirely within China, and was also a boost to women scientists. Surprisingly, Tu was never elected to the CAS. The reasons are still obscure. One lame excuse is that she is past the normal age for election to the Academy, but she was just over 40 when the key discovery was made. The strong-willed lady probably rubbed some people the wrong way. There might also have been some feeling that the achievement was more a group effort than a uniquely personal triumph. After all, it was a top-down national project, with a division of labour on different candidate herbs; Tu happened to get her hands on the one that worked. No doubt there is some truth in such an assessment, but it is equally true that wormwood would have slipped through the fingers of a less talented scientist, for example, if cold extraction had not been tried. Be that as it may, the nation made up for the omission[8] with very high-level awards: the Highest Science and Technology Award in 2016 and the even more prestigious Medal of the Republic in 2019.[9] Incidentally, it has been suggested that artemisinin may be useful in combating COVID-19 (Fuzimoto, 2021).

[7] For context, recall that North Vietnam was at war with the US, with soldiers often trekking through mosquito-infested jungles.

[8] Election to the Academy, for all the faults that one can find, is a truly democratic process, and the State is unable to control the outcome.

[9] Winners of the Highest Science and Technology Award number fewer than 20. The nine winners of the Medal of the Republic include Yu Min for nuclear bombs, Yuan Longping 袁隆平 for hybrid rice, and Zhong Nanshan 鍾南山 for contributions in the SARS and COVID epidemics.

Chapter 5

Recent achievements

5.1 Age of reform and opening up

The political watershed

Science and technology, indeed the entire society in China, went into a period of rapid development after the political transition starting in 1976 and marked by a turn towards a policy of reform and opening up under the leadership of Deng Xiaoping 鄧小平.

Significant policies were announced at the Third Plenum of the 11th Central Committee held in August 1978. For the first time, modernisation (rather than revolution or class struggle) was placed high on the agenda (CPC CC, 1978, Sect. 1); economic development and technology innovation were given attention; the Four Modernisations[1] were cited (in the order agriculture, industry, defence, and science and technology). Very importantly for our discussion, the Plenum affirmed the principle that "practice is the only criterion to judge truth" (CPC CC, 1978, Sect. 4), negating the earlier call under Hua Guofeng 華國鋒 of the "Two Whatevers" 兩個凡是: to follow without question whatever Mao 毛澤東 had said.

One might regard the issue as merely philosophical; nevertheless there were enormous consequences. In a sense, it was a much delayed and compressed version of the same debate and the same transition that had heralded the advent of the modern age in Europe. The medieval standard was "Whatever the Bible says is the truth", a point of view which stood in the way of scientists (and would-be scientists) all the way to Galileo (c. 1615). Only when the "Whatever" was given up could modern science arise in Europe, with the growth of empiricism (e.g., Bacon, c. 1620), rationalism (e.g., Descartes, c. 1640) and finally the Enlightenment call: "Dare to know! Have the courage to use your own intelligence!" (Kant, 1784).

[1] The term had in fact been used in the early 1960s, but became an important rallying call only from 1978.

The change in the political landscape impacted science in at least three ways. (1) There was immediately a sense of liberation and purpose among scientists. (2) The slow task of rebuilding academic institutions began. (3) The resultant gains in the economy over the next decades drove a virtuous cycle with steady improvements in education and in science and technology.

Rebuilding institutions

Universities had been devastated during the Cultural Revolution. Many professors were humiliated. Scholars and students were sent down to the countryside to be re-educated. The scholars had started to return in the later years of the Cultural Revolution; the flow accelerated with the change of national policy, and universities as well as research institutes were re-staffed. A crucial event was the re-establishment of a nation-wide examination system (now *gaokao* 高考) for selecting students to higher-education institutes — in the years of the Cultural Revolution, selection had been based on recommendations from villages, factories and work units, often emphasising perceived political correctness. The first examination under the new system, held towards the end of 1977, was met with enthusiasm among the most capable young people. The initial cohorts were of specially high quality, filling a relatively small quota from the pent-up demand of a whole decade.[2] However, for some ten to fifteen years, funding was scarce, facilities were inadequate, and contact with the outside was limited.

The Spring of Science

In March 1978, at the closing of the Science Congress, Guo Moruo 郭沫若,[3] President of CAS, made a famous speech entitled "The Spring of Science" 科學的春天, which captured the positive mood among scientists at that time.

> The Chinese people have made outstanding contributions in the history of human civilisation. ... [Now] we need not only giants in politics and culture, but also giants in natural science and in other domains.
>
> (Guo, 1978)

[2] Thus, students of those few cohorts spanned a fairly large difference in age. They were not only academically excellent, but must have been also the most resilient, often having studied on their own under difficult circumstances.

[3] Guo, better known as a man of letters, was a scientist only by a liberal interpretation of the term: the closest he came to science as now conventionally defined was through his interest and expertise about ancient texts — which bordered on the science of archaeology. He has at best a mixed reputation, being often regarded as spineless during the Mao years. Nevertheless, the scientific community thought highly of this particular speech.

5.2 Economic development and other indicators

Economic growth

The years following the reform and opening up witnessed a phenomenal rate of economic growth, unequalled in human history (except possibly for small regions or for short periods of time). The comparison with the US shown in Table 5.1 (and the comparison would be broadly the same for other developed economies) tells the story at a glance: whereas the US economy expanded by a factor of 7 over 40 years, the Chinese economy expanded by a factor of 70! Moreover, the present gap of about 2-to-3 is closing rapidly, and the Chinese GDP is projected to surpass the US GDP within this decade (and in purchasing power parity terms may have already done so) — even though there is still a large gap in per capita terms.

	China	US
1980 GDP (USD trn)	0.2	2.9
2020 GDP (USD trn)	14.7	20.9
Multiple in 40 years	70	7

Table 5.1: GDP of China and US in 1980 and 2020, in USD trillion. Data from World Bank (2021a).

The economic expansion went through several overlapping stages. Productive energy was immediately unleashed when the collective economic system was relaxed and then essentially abandoned. Next, low-end industries took off, in many cases relying on the low cost of labour. Industries with more technology content were introduced, initially often with outside partners who brought both capital and know-how, and later with widespread growth of indigenous establishments, so that China is now the "workshop of the world" — a term that was used to describe 19th century Britain (Hudson, 2011). Then proprietary intellectual property propelled new products, launching an economy increasingly driven by innovations. Obviously technology (if not science) played an important role in the later phases. Science and innovation are necessary ingredients for moving up the value chain and avoiding the middle-income trap (ADB, 2017).

The story of the automobile industry, especially for passenger cars, illustrates well the stages in this process. In the early 1980s, China had only a few antiquated automotive works, their output supplemented by Soviet imports also of low quality. Then joint ventures were established, e.g., with American Motor Corporation in Beijing, with VW in Shanghai and with Peugeot in Guangzhou, followed by other brands such as Toyota and Nissan. With key technologies withheld, these joint-ventures were little more than assembly plants. A number of domestic manufacturers emerged, but none was very successful. As a result of growing demand, imports soared, despite heavy duties. More recently, domestic enterprises took advantage of the disruptive electric vehicle (EV) re-

volution powered by the need to reduce carbon emission.[4] In 2021, Chinese producers SAIC and BYD are respectively third and fourth globally in terms of plug-in EV sales,[5] coming in after Tesla and VW (INSIDEEVS, 2021a). BYD is especially impressive in its integration of artificial intelligence (AI) and a novel battery design, with rumours in the market that Tesla may be buying BYD batteries (INSIDEEVS, 2021b).

The economy intersects with science and technology in other important ways, though the results will take longer to become manifest. There is now the revenue to invest substantially in R&D, so that society enters a virtuous cycle with economic growth and technological advancement propelling each other forward. In the longer term, increasing affluence in society will allow a shift of emphasis, both socially and individually, away from concerns about immediate utility (this generation is probably the first in Chinese history not to worry about the next meal) and towards pursuits driven simply by curiosity about nature, which will in the long run benefit basic science.

Scientific productivity

Keeping pace with the size of the economy, quantitative indicators of scientific productivity have also risen sharply, in many cases ranking within the top one or two in terms of total output. China is now number one in scientific and technical journal articles published, some 20% ahead of the US and at least 4 times more than nations in the next tier: India, Germany, Japan, UK and Russia (World Bank, 2021b). In patent applications, the numbers are even more remarkable: China is number one, with the US and Japan at one quarter, followed by Korea, Germany, Russia and India at a mere fraction (World Bank, 2021c).

Such data are on the one hand encouraging, but must on the other hand be read with caution. First, the statistics on a per capita basis is less impressive. Second, there is much more of a bean-counting culture in China, such that scientists have a sometimes perverse incentive to publish or to seek patents whether or not the result is particularly worthwhile or interesting.[6] This observation hints at two challenges for the years to come: (1) emphasis on quality rather than quantity, and (2) shifting recognition and rewards from bureaucrats (who can only understand hard numbers, or worse yet, only media hype) to independent peers.

[4] There should be a health warning in relation to the hype about reduction of CO_2 emission. It is true that the EVs as such do not emit CO_2, but the power plant producing the electrical energy does — and may even cause *more* emission of greenhouse gases if the plant is coal-fired.

[5] Not restricted to passenger cars.

[6] If your grade is pegged to the number of words in your term paper, you will no doubt write at great length, whether or not you have anything to say.

5.3 Recent achievements in science and technology

The statistics should be given flesh and blood by specific examples of notable recent achievements. In certain fields, China is acknowledged to be world-leading: electronic payments and high-speed trains come to mind — not necessarily that other countries cannot do it, but that they have not done it, perhaps for reasons other than technological capability. In implementation of 5G communication technology, Huawei 華為 is certainly a world leader, so much so that there are underhand tactics to destroy the company.[7] In artificial intelligence (AI), China is also regarded as leading (Marr, 2021; Li, Tong & Xiao, 2021). SenseTime 商湯, an AI company spun off from CUHK, had its stock listing in Hong Kong in late December 2021 almost sabotaged.[8]

Achievements in space exploration have received wide attention. Possibly the most important (if not the most spectacular) is the Beidou 北斗 navigation system (three generations in 2000, 2011 and 2015) which now provides an alternative to the US, European and Russian counterparts. Missions to the Moon are named in the Chang'e 嫦娥[9] series (Table 5.2).

Sequence	Year	
1	2007	orbited Moon
2	2010	orbited Moon
3	2013	landed on Moon
4	2018	landed on backside of Moon
4	2020	landed and returned with 1.7 kg of sample

Table 5.2: Chinese Moon missions in the Chang'e series.

The first astronaut went into space in 2003.[10] Several missions later, Chinese astronauts are now spending months in a large space station (Tiangong 天宮).[11] A probe to Mars was launched in 2020, landing a rover to explore the Martian surface.

On another frontier, an unmanned submersible reached a depth of 10,000 m, almost equal to the maximum depth of the oceans and essentially matching the

[7] However, Huawei was able to announce 76% increase in profit in 2021.

[8] US investors including investment funds were forbidden to take up shares. In the end, the sudden ban caused only a short delay to the IPO. Ironically, the ban was seen as an implicit endorsement of technical superiority, and helped to push the share price up by some 40% one week after the IPO.

[9] Chang'e is the mythological goddess of the Moon.

[10] At least two billionaires with large egos (Bezos and Branson) have orchestrated flights as private enterprise. So one might be led to think that space flights are no longer such big deals. However, these "flights" only put vehicles up beyond the atmosphere and allowed passengers to experience some minutes of weightlessness when the rockets were turned off; the vehicles did *not* orbit the Earth — as all genuine astronauts do.

[11] At the time of writing in December 2021, three astronauts are in Tiangong-2, and are expected to return after a six-month stay.

record of several countries, some of which have also deployed manned submersibles (though the scientific advantage of the latter is not obvious).

In civil aviation, the regional jet ARJ21 (capacity of under 100 seats, range about 3,000 km, designed in China but using General Electric engines) has come into domestic service. The larger C919 (about 150 seats, range up to 3,000 km, designed in China and using LEAP engines from a US–French consortium) will be a competitor to Airbus 320 and Boeing 737, thus projecting the Chinese aviation industry into the ABC triumvirate as its junior member.[12] The yet larger C929 (about 300 seats, up to 12,000 km range, either Rolls Royce or General Electric engines) is in design and prototype stage, and should come into use within this decade, competing in the same arena as Airbus A330 and Boeing 787. Many key components rely on external suppliers, though Airbus and Boeing also outsource.

In moving away from fossil fuels, China is dominating in photo-voltaic (PV) production (Buchholz, 2021); has the largest installed wind power capacity of over 350 GW (Unwin & Farmer, 2021), more than double that for the US in second place,[13] and built half the world's wind-farms in 2020 (Ambrose, 2021); and is third in the world in terms of installed nuclear power capacity, after the US and France (Kumar, 2021). Nuclear energy again illustrates the stages of development. The first modern plant is the one at Daya Bay (start of construction 1987, commercial operation 1994); some of our electricity supply in Hong Kong comes from this plant. This pioneering plant was a French reactor.[14] Not only was there a technology gap, but foreign currency was also a problem at the time — thus China Light and Power (CLP) in Hong Kong was brought in, to take up 70% of the output, and, not incidentally, to bring in its management experience. Later installations (e.g., the CPR-1000 version) were Chinese-built reactors with core technology licensed from the French. A further evolution to proprietary technology led to versions (such as the ACP-1000) that could be exported. Now, there are efforts to design novel reactors that are smaller, more efficient and endowed with better intrinsic passive safety features.[15]

The list of achievements can hardly be exhausted, but the above examples should suffice to paint an overall picture of the advances made since the reform and opening up.

[12] ABC has come to mean Airbus, Boeing and Comac (Commercial Aircraft Corporation of China) 中國商用飛機有限責任公司，商飛.

[13] A typical coal-fired or nuclear power plant is about 1 GW or less.

[14] But the second stage where the reactor thermal output drives a conventional steam turbine is British — not that the French could not have built it all in one go, but before 1997, CLP in Hong Kong was subject to arm-twisting by the UK government.

[15] Namely, shutdowns relying on physics rather than engineering or operator intervention.

Chapter 6

Basic science

One may be struck by the dearth of examples drawn from basic (i.e., fundamental) science, or at least science rather than technology. First, it is necessary to remark that the tilt towards technology (rather than science) does not originate from a bias in my choice of examples; most Chinese commentators, including official media and state leaders, would point to a largely similar list — thus reflecting not only the balance of achievements, but also the balance of what is *regarded* as important. Second, if one looks at achievements in basic science at very high levels, it is unfortunately true that very few can be found.

To make this statement somewhat objective and to avoid any bias, especially self-congratulatory wishful thinking, a selection will be made based on winners of major international prizes.[1] There is of course Tu Youyou's Nobel Prize in 2015, but that work was done in the 1970s. If one considers discoveries in this century, only two works done in China have been associated with these major prizes: the transmutation of neutrinos and DNA in blood plasma, winning the Breakthrough Prize respectively in 2016 and 2021. For the former, China had roughly a half share, within which CUHK contributed a part; the latter is entirely a CUHK project, still going towards further impacts. While one should celebrate these achievements (and CUHK's role in them),[2] one must at the same time lament that *there is nothing else that can be cited.*

[1] Of course one starts with the Nobel Prizes in science (about USD 1 million). Then there are the Breakthrough Prizes (up to USD 3 million, but often shared across several teams, each of which may also be large). The Shaw Prize (USD 1.2 million) is awarded in astronomy, life science & medicine, and mathematics. The Kavli Prize (USD 1 million) is awarded in astrophysics, nanoscience and neural science. The Abel Prize (about USD 0.8 milion) is awarded in mathematics. The following smaller prizes are not included. The Lasker Awards in medical sciences is prestigious, but quite a bit smaller (USD 0.25 million). The Fields Medal is limited to young mathematicians and carries a modest sum (about USD 15,000).

[2] No effort is made to deliberately highlight our own university; the selection is objectively based on the list of major prizes.

6.1 Neutrino transmutations

(I thank Prof MC Chu for commenting on a draft of this part.)

Neutrinos are elusive particles that hardly interact, and are therefore difficult to detect. They were first proposed by Pauli in 1930 as an undetected particle to explain the missing energy and momentum in β decays.[3] The first variety ν_e was found in 1956,[4] a second variety ν_μ was discovered in 1962 and a third variety ν_τ (by that time expected) was discovered in 2000. Nobel Prizes were awarded for the first two discoveries.[5]

Neutrinos (ν_e) are also produced as a byproduct of the fusion process which powers the Sun and the ratio of neutrinos to the energy production can be predicted by known nuclear physics and reliable solar models, but the flux when measured on Earth was only half of what was expected.[6] Eventually the accepted explanation is that one variety of neutrinos can transmute into another, and about half of the ν_e had turned into other varieties on its way from the Sun; the detector is sensitive only to the original variety ν_e. The rates of transmutation are determined by three parameters called mixing angles. The two larger ones θ_{23} and θ_{12} were quickly measured. The Daya Bay 大亞灣 experiment was designed to determine the last small one θ_{13}.

As with all high energy experiments,[7] hundreds of scientists were involved, from many institutions across many countries. The two major teams were respectively from China, led by Wang Yifang 王貽芳 of the Institute of High Energy Physics and from the US, led by KB Luk 陸錦標[8] of the University of California at Berkeley; they were the two named recipients of the Breakthrough Prize. Other members of the team included MC Chu 朱明中 and his experimental group at the CUHK Physics Department.

The idea is that nuclear fission in reactors produces a flux of (anti-)neutrinos. Detectors are set up at different distances, and if the measured flux departs from an inverse-square relationship with distance, that would be evidence of transmutation into other forms. The Daya Bay experiment, despite a later start, had several advantages over French competitors, including the following. (1) At Daya Bay, there were six reactors in a cluster (versus only two in the French case), so there was a stronger beam of neutrinos to start with. (2) The Daya Bay detectors were much larger, giving rise to a proportionately larger number of events. (3) There happens to be a small hill nearby (versus flat country for the French), so that when instruments were placed in a tunnel dug into the

[3] Actually in β decay, an *anti*-neutrino is emitted, but we shall gloss over this distinction in this account.

[4] Based on a method first suggested by Wang Ganchang 王淦昌 more than a decade earlier, before he returned to China. See Table 3.2

[5] There is a famous saying by Fermi that "Experimental confirmation of a prediction is merely a measurement."

[6] The other half of Fermi's famous saying is "An experiment disproving a prediction is a discovery."

[7] This is the term conventionally applied to this branch of experimental physics, though in the case of solar or reactor neutrinos, the energy is actually quite low.

[8] KB Luk was originally from Hong Kong.

hill, the overlay of rocks filtered away most of the cosmic rays, removing the "noise" that would confound the signal.[9] In the end, the Daya Bay experiment was the first to report accurate results (An et al., 2012, 2013), and, as already mentioned, won the Breakthrough Prize a few years later.

One might be tempted to ask: What is the practical use of this discovery? The short answer must be "none" — though there could be long-term spin-offs from the technology developed from the needs of the experiment; it is perhaps not widely known that the World Wide Web grew out of the need to share data across continents in such high-energy experiments. However, such applications are byproducts; scientists are driven simply by curiosity about nature: in this case how elementary particles interact and whether these elusive particles play a significant role in the evolution of the universe.[10]

In this connection it is worth citing a well-known episode in the US, also about high-energy physics. In 1969, Wilson was among a group of scientists testifying before a Congressional committee to seek funding for a new accelerator. One senator asked whether the project would benefit "the security of the country". Wilson answered "no", and the senator was obviously not satisfied. The further answer by Wilson has become famous as a celebration of basic science:

> It has only to do with the respect with which we regard one another, the dignity of man, our love of culture. It has to do with: Are we good painters, good sculptors, great poets? I mean all the things we really venerate in our country and are patriotic about. It has nothing to do directly with defending our country except to make it worth defending.
>
> (Wilson, 1969, in Congressional testimony, as reported in *APS News*, 2018)

6.2 DNA in blood plasma

(I thank Prof Dennis Lo for commenting on a draft of this part.)

We all "know" two "facts": (1) DNA resides *inside* cells, and (2) the blood circulations of a foetus and its mother are separated by the placenta and do not mix (the two can have different blood types). Dennis Lo 盧煜明 of the CUHK Faculty of Medicine showed that neither of these textbook statements is strictly true. As a result, traces of foetal DNA[11] leak from the cells into the foetal bloodstream, and across the placenta into the maternal bloodstream. This phenomenon was first confirmed in a clever and relatively simple experiment: a tiny amount of XY chromosomes (characteristic of males) was found in the

[9] Other differences are glossed over.

[10] Neutrinos, especially since the transmutation implies that they must have some mass, are certainly a part of the dark matter that is important in the evolution of structure in the universe, including the formation of galaxies and ultimately the emergence of life.

[11] In fact, also RNA, but both of the applications cited below rely mainly on DNA.

blood of pregnant women who eventually gave birth to boys, but not in those who gave birth to girls.

As a result of these fundamental discoveries, one can now do genetic testing on the foetus by just drawing a small quantity of blood from the mother, without invasive procedures (Lo et al., 2010);[12] the obvious application is testing for Down's syndrome in early pregnancy. This test is now offered routinely by the Hospital Authority in Hong Kong, and is used worldwide under licence authorized by CUHK. For this work, Dennis Lo was awarded the Breakthrough Prize in 2021.

The next stage of investigation promises to be even more important. If one thinks of the foetus as a "foreign" object whose presence can be detected by the leakage of DNA into the bloodstream, might not the same be true for other foreign objects such as malignant tumours? Lo and collaborators were able to confirm the following (Lam et al., 2018): in patients treated for nasopharyngeal cancer, those with detectable levels of tumour-related DNA fragments in blood are prone to relapse (and should therefore be given further aggressive treatment such as chemotherapy), even when no remaining tumour can be detected by conventional means such as X-rays. The novel test is much more sensitive because it operates at molecular rather than macroscopic level, and promises to reduce fatalities not only for relapse, but also for screening of high-risk groups. Early diagnosis through cell-free nucleic acid is already offered commercially.

An overview of these developments can be found in Lo et al. (2021).

6.3 Reasons for weakness in basic science

Possibly the single most important issue for the long-term future of science and technology in China is to understand the reasons for weakness in basic science — and to seek remedies. To the extent that this issue also relates to the scientific spirit, there are also ramifications that go beyond the scientific community, with potential impacts on society at large. There is of not a unique reason, or a definitive and exhaustive list that all commentators agree on. But a number of factors come to mind.

There is the Confucian tradition (whether or not all this can be attributed to Confucius himself): a possibly excessive respect for authority and the ways of old,[13] and (less often remarked) an overwhelming concern with ethics and society that marginalises interest in nature. The Daoist fondness for vague correlative reasoning and disinterest in precision cannot escape a degree of responsibility. Hu Shih 胡適 (1919) famously caricatured this attitude in the satirical essay "Mr Almost-the-Same" 差不多先生.

The pragmatic attitude prevalent throughout society has been remarked by

[12] Otherwise the standard test would involve amniocentesis: inserting a needle into the mother's abdomen to extract some fluid from the womb, a procedure that carries some risk of harming the foetus.

[13] Thus, "innovation" would not be in the vocabulary, much less "disruption" as a term of praise.

many commentators. Thus, there has traditionally been little inclination to ask "why", so long as some method or process works. In a sense, one cannot fault the focus on practical results when survival was not assured — as already remarked, it is only in the last few decades that Chinese society as a whole has been able to set aside its worries about hunger. To spend time and effort on questions purely for the sake of curiosity about nature is a luxury that only an affluent society (or an affluent and privileged sector within society) can afford.

The centrally planned economy is on the one hand positive for targeted initiatives, especially large projects that require coordination and commitment of long-term resources, but is on the other hand not friendly towards truly innovative basic science — which by definition explores the unknown and cannot really be "planned". The hierarchical nature of the research community (with bureaucrats at the top) means that working scientists are driven to respond to key performance indicators (KPIs) expressed in hard numbers: the quantity of publications, citations,[14] patents and grants, which, when carried to extremes, surely deter true scholarship.

Achievements in science necessarily suffer a delay with respect to expenditure in R&D. Lau and Xiong 劉遵義, 熊艷艷 (2022) have argued that scientific output, as measured for example in terms of patent applications and grants in any period, is determined not by the contemporary level of expenditure, but by the *cumulative* investment over a period in the recent past.[15] The economic argument is about science in general, but the conclusion must apply *a fortiori* to basic science. Indeed, there is an element of accumulation beyond the economic dimension. In many examples cited in this lecture, those who have made important contributions had benefited from a good university education in China, which in turn depended on credible departments and centres established by an earlier generation of scholars. To the extent that this factor relating to delayed impact carries weight, one can look to the coming decades with a degree of optimism.

[14]There is a preoccupation with the Science Citation Index (SCI). Yang Fujia 楊福家, formerly President of Fudan 復旦 and later Chancellor of Nottingham University in the UK, has called the SCI a "Silly Chinese Idea" (Yang, private communication).

[15]Just as a student's performance in an examination is not determined by the effort devoted to study in the preceding week, but could be related to diligence in years past, perhaps even extending to childhood.